Structural Requirements and Scaling Analysis of a Fluidic Mirror Space Telescope Support Structure

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Abstract—**The NASA FLUTE project proposes large-scale (50m) fluidic telescopes for astronomy applications. To continue to explore the universe, astronomers require larger and larger telescope apertures. The highest priority astrophysics targets such as exoplanets and early galaxies are extremely faint, motivating larger telescope apertures. However, mission costs depend on aperture diameter, and scaling apertures beyond 10-m apertures faces economic and technological viability challenges. An unsegmented primary mirror made in space via fluidic microgravity shaping would provide a scalable and cost-effective method to scale apertures to 50-m scale while achieving sub-nanometer (root mean square) surface quality. Such microgravity fluidic shaping has been demonstrated in laboratory neutral buoyance environments, parabolic microgravity experiments, as well aboard the International Space Station. One of the main components of a fluidic observatory is the mirror frame. The frame must provide a stable bounding circular ring which the edges of the fluid mirror surface can wet. The frame can optionally provide a 'floor' surface on the interior of the ring to provide additional fluid support and reduce required fluid volume. In this work, we evaluate several classes of structural frame architectures potentially suitable for a fluidic telescope support structure. We start by estimating stability requirements, orbital, station keeping, and slew loads based on a notional CONOPS. The scaling of overall fluid mass required for each architecture is evaluated. Preliminary results elucidate the importance of a support floor for overall mission viability above 10-m diameter. We then investigate the scaling of a tetrahedral truss frame support structure. We show that segmented solid shell support surfaces can provide sufficient stability at modest mass fractions. We estimate that the total fluid and frame mass for a 50-m telescope could be on the order of 15,000 kg. Finally, implementation considerations are discussed, including deployment/assembly methodologies. The results of this study establish feasibility of a large-scale fluidic telescope and will guide further architecture development and detailed structural design.**

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1. INTRODUCTION

To continue to explore the universe, astronomers require larger and larger telescope apertures. The highest priority astrophysics targets such as exoplanets and early galaxies are extremely faint, challenging the capabilities of current and future observatories. Larger aperture diameters are one of the only ways to address this challenge. However, mission costs depend on aperture diameter, and scaling beyond 10-m apertures leads to economic and technological viability challenges given anticipated launch vehicle capabilities.

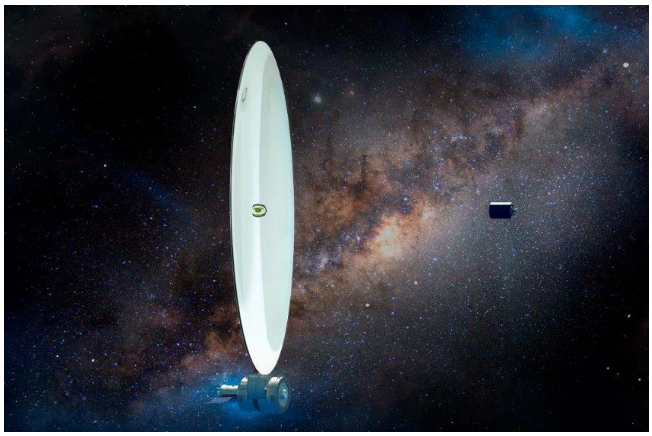


Figure 1. Early concept rendering of the Fluidic Telescope (FLUTE).

The Fluidic Telescope (FLUTE) is a mission concept for a space observatory with a large-aperture (50-meter), unsegmented primary mirror, suitable for a variety of astronomical tasks, including high-sensitivity atmospheric spectroscopy of extra-solar planets. The mirror would be created in space via a novel approach based on fluidic shaping in microgravity [1], [2], enabling extremely large unsegmented optical components with sub-nanometer root mean square (RMS) surface quality.

In this paper, we first provide background on fluidic lens shaping, the benefits of a fluidic mirror for a space telescope,

and the typical structures required to implement the concept. We then discuss the requirements for a fluidic mirror observatory within a mission concept of operations, focusing on structural frame requirements. Finally, we discuss our modeling approach and results of the volumetric scaling analysis and first-order structural analysis.

2. BACKGROUND

Fluidic Shaping

The FLUTE concept proposes the use of fluidic shaping to create large optical components in microgravity. Fluidic shaping leverages surface tension phenomena in microgravity to shape a liquid into a desired optical form with sub-nanometer surface quality. A liquid with appropriate optical properties is brought into contact with a high-affinity bounding frame, resulting in pinning of the liquid to the frame. In microgravity, the shape of the free surface is dictated solely by surface tension, thus assuming the shape of a spherical cap. Further dynamic control over the shape is possible through changing the liquid volume, the frame geometry, and — if desired — with the addition of external forces (e.g., electromagnetic). Both refractive and reflective components can be created. Optionally, if the liquid can be solidified (e.g., a liquid metal), the resulting component can then become an optical-grade solid object, without post-processing steps. However, leaving the component liquid also provides advantages, including the ability to recover full optical quality after micrometeoroid strikes. The fluidic shaping method is scale-invariant, limited only by the size of the bounding frame, the amount of available liquid, and the allowed deployment time. This method has already been successfully demonstrated in a laboratory neutral buoyancy environment, where components of different optical geometries and sizes have been produced [1], [2], in the microgravity environment of parabolic flights[3], and aboard the International Space Station (ISS) [4].

Fluidic Telescope Motivation and Structural Challenges

The fluidic shaping approach used for FLUTE provides a unique capability to create very large-scale unsegmented reflectors. Because of the surface tension at the free surface of the liquid, the surface quality of these components is excellent, with sub-nanometer RMS error that is decoupled from the surface error in the support structure. In fact, certain dimensions of the support structure can have quite large shape imperfections and still yield a sub-nanometer RMS surface, so long as the volume of fluid is thick enough to cover these imperfections.

Structures of the scale required for a 50-m fluidic telescope have been proposed and produced. Astromesh reflectors are available at 50 m. Inflatable architectures have been flown at >10-m scale [5]. However, the FLUTE support structure has unique requirements. Most structural solutions focus on large-scale radio reflectors that feature lightweight mesh layers that are on the order of tens of grams per meter squared. Depending on the fluid used (which could be gallium alloys or ionic liquids), the areal density in the case of FLUTE will be at least two orders of magnitude larger. Designs for structures that must control thousands of kilograms of liquid layer under slewing and station-keeping loads have not been adequately assessed.

4. MODELS AND APPROACH

Notional CONOPS

While our general approach allows for creation of either lenses or mirrors, we chose a mirror as the primary optical surface for its greater versatility and better mass efficiency. We also chose a mirror that remains liquid over a solidified one. A solidified mirror has higher structural rigidity and could allow for a wider range of observable wavelengths (including infrared); however, a liquid mirror has its own advantages. As mentioned above, its geometry can be changed dynamically, and it is also more tolerant to problems arising during deployment, as well as to damage via extraneous factors (e.g., micrometeorites). We assume that the telescope will operate in Earth-Sun Lagrange point L2 halo orbit. While, theoretically, lenses or mirrors of virtually unlimited sizes can be created using our approach, for the purposes of the proposed study we constrain the mission concept to a single payload that can be launched with a heavy lift launch vehicle (e.g., SpaceX Starship or NASA Space Launch System) from Earth. We further assume that the vehicle can be refueled in LEO, allowing it to deliver approximately 100+ metric tons to L2.

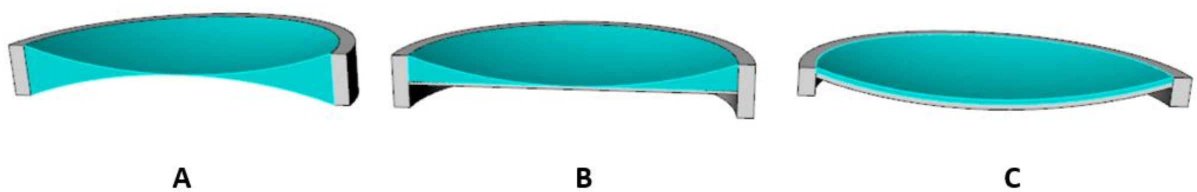


Figure 2. Frame archetypes considered for a fluidic telescope support. Grey is frame structure and blue is fluid. The most basic support type is a simple bounding ring (A). An optional support surface can be added to reduce the necessary fluid volume. This support surface can, for example, be flat (B) or curved (C).

The fluidic telescope will consist of a main spacecraft bus, reflective fluid tank, deployable or assemblable frame, sunshield, and instrumentation module. The instrumentation module may be a separate spacecraft to be flown in formation with the large reflector surface or held at the focal point via deployable booms. The frame will have a bounding ring, as well as an optional support 'floor' surface to which the fluid will wet. After frame deployment or assembly, fluid will be pumped onto the frame via fluid transfer lines integrated into the structure. To maintain a liquid fluid, we anticipate heating elements will also be included into the frame ring or optional floor surface.

Requirements

We consider three basic frame archetypes (Figure 2). The most basic requirement of the frame is to provide a bounding ring which the fluid will wet; it is present in all frame types. An optional support surface (floor) can be added to reduce the necessary fluid volume. This support surface can, for instance, be flat (Figure 2.B) or curved (Figure 2.C); in our modeling we assume a spherical support surface (since this will minimize volume). Regardless of the floor geometry, a spherical reflecting surface is created, the curvature of which is governed by the volume of the fluid. For a perfectly spherical support structure, a constant thickness fluid film would cover the surface. However, most deployable or assembled structures approximate doubly curved surfaces (for antennas, etc.) using flat triangular surfaces. In this case (Figure 3), the fluid thickness would not be perfectly constant across the surface, but would still drastically reduce the fluid volume required for a given radius of free surface curvature when compared to the other frame archetypes. Notably, by ensuring enough fluid thickness, imperfections of the support surface shape can be accommodated with no influence on optical surface quality. Defects in the ring geometry can create localized imperfections on the free surface which should diminish quickly with distance from the outer bounding ring. Volumetric scaling of each frame type can be assessed via straightforward geometric analysis. To simplify analysis, we assume that a curved surface in a Type C frame will be approximated with enough resolution that the fluid volume can be estimated by assuming constant fluid thickness across a spherical support surface.

The ring of the frame, as well as an optional support surface, must provide sufficient stability during station keeping and slewing to avoid fluid rupture. Secondary to fluid resistance to rupture, the structure may need to maintain certain minimum stability during slewing or station-keeping loads to ensure that the fluid can settle in a reasonable amount of time. The frame and the resultant fluid surface must also be precise enough so that the wavefront produced by the static surface shape of the fluid can be sufficiently corrected by adaptive optics. For low frequency variations, we assume this limit to be 10 microns.

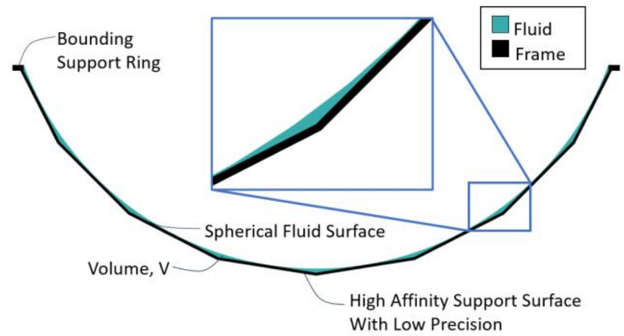


Figure 3. Notional illustration of how the fluid surface can smooth frame imperfections and is insensitive to the frame surface quality. The fluid will wet the frame support structure and form a perfect spherical section surface, the curvature of which is governed by the volume (assuming a sufficient volume to cover imperfections of the support surface).

Analytical Structural Analysis

Investigating the first order mass-scaling of frame structures for a fluidic telescope, we focus on the minimum volume frame archetype. In "Rationale for Defining Structural Requirements for Large Space Telescopes," Lake et al. [6] establish back-of-the-envelope approximations for telescope structural performance. The equations and associated explanations in this section are taken directly from Lake et al. [6]. A key finding is that an upper bound for the root mean square (RMS) deformation in a telescope mirror due to quasi-static inertial load, x_{rms}, is given by

$$x_{rms} \le \frac{a_{rms}}{4\pi^2 f_0^2} \tag{1}$$

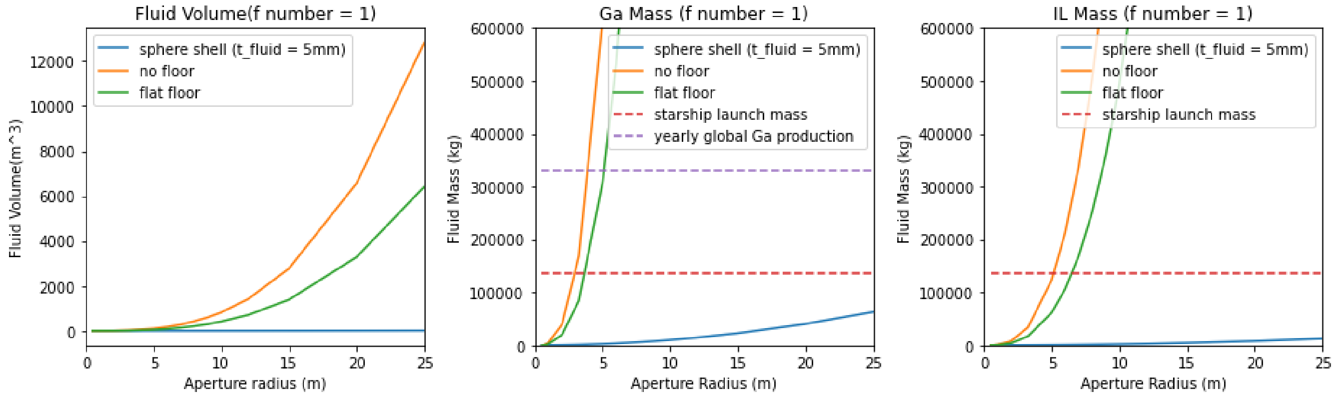
where f_0 is the fundamental natural frequency of the telescope mirror (in hertz) and a_{rms} is the RMS magnitude of the acceleration associated with the disturbance load. Lake et al. also provide formulations for the upper bound deformations due to slewing, gravity gradients loads, and solar pressure loads. The RMS deflection due to slewing is given by

$$(x_{rms})_{slew} \le \frac{d}{2(f_0 T_{slew})^2} \tag{2}$$

where d is the diameter of the aperture, T_{slew} is the period of the constant-rate slew (relative to an inertial reference frame). An upper bound for the RMS magnitude of elastic deformation due to solar pressure is given as

$$(x_{rms})_{solar} \le \frac{\alpha}{f_0^2 \rho_{areal} R_{solar}^2} \tag{3}$$

where ρ_{areal} is the areal density in kg per square meter, and R_{solar} is the distance from the space craft to the sun in astronomical units (AU). The α is equal to $2.28 \ x \ 10^{-7}$ N and comes from making worse case assumptions regarding the interaction between the "incident photon flux and the spacecraft surface" [6].



(a) (b) (c)

Figure 4. Volume scaling of the three archetypal frame structures. (a) The fluid volume necessary for each frame type. (b) The fluid mass necessary assuming gallium. (c) The fluid mass necessary using ionic liquids (IL).

For dynamics studies of structures in the case of a thin film on a curved support structure, we assume that the natural frequency of the support structure with the fluid film is well approximated by the natural frequency of the support structure with the mass loading of the fluid film [7].

We seek a simplified structural model for the curved frame (frame archetype C), assuming a relatively shallow radius of curvature, to provide analytical 'back-of-the-envelope' estimates of the structural mass. Lake et al. established that the fundamental frequency of a tetrahedral truss supporting segmented solid mirror panels is well approximated by the analytical model for a vibrating plate, assuming the plate material to be the density and stiffness of the cellular solid formed by the tetrahedral truss. The fundamental frequency of this structure in hertz is given by

$$(f_0)_{segmented} = \left(\frac{\gamma}{d}\right)\left(\frac{h}{d}\right)\sqrt{\eta\left(\frac{E}{\rho}\right)_{truss}}, \qquad (4)$$

where d is the diameter of the plate (aperture diameter), h is the thickness, η is the structural mass fraction defined as

$$\eta = \text{truss mass / total mass} \qquad (5)$$

$(E/\rho)_{truss}$ is the specific stiffness of the truss. The constant γ=0.852 is a geometry factor (see derivation in [6], which is derived from analytical plate vibrational frequency relationships). Though this is for a tetrahedral truss, we assume that this can be used to conservatively estimate the fundamental frequency of a circular support truss that bears the load of carbon fiber segmented panels that, in turn, support a fluid layer (Figure 5). This assumption is well supported by analytical models for the vibrational frequencies of circular and hexagonal plates, especially for the first order analysis conducted in this work. This model can be expected to be conservative, considering the stabilizing effect of the curvature, as well as the structural contributions of the carbon fiber support panels. This conservative approach is appropriate for initial analysis, given the uncertainty of mass of fluid lines, potential heating elements, and other functional elements that may need to be incorporated. Like Lake et al., we assume that the support truss is made of a composite material with E= 104 GPa with a density ρ = 1700 kg/m^3. This gives $(E/\rho)_{truss}$ of 61.2e6 m^2/s^2.

We consider two mirror liquid options: gallium (or one of its alloys) and an ionic liquid infused with reflective nanoparticles. Gallium is a highly reflective, non-toxic metal with a melting temperature of ~30 deg. C. When liquid, its density is ~6,000 kg/m^3. Our second option, ionic liquids, have been previously considered for space-based telescopes, albeit in spinning-mirror architectures [8], [9]. They generally have very low evaporation rates in a vacuum, remain liquid at low temperatures, and have densities 4-5 times lower than gallium [10]. We will assume an ionic liquid density of 1200 kg/m^3.

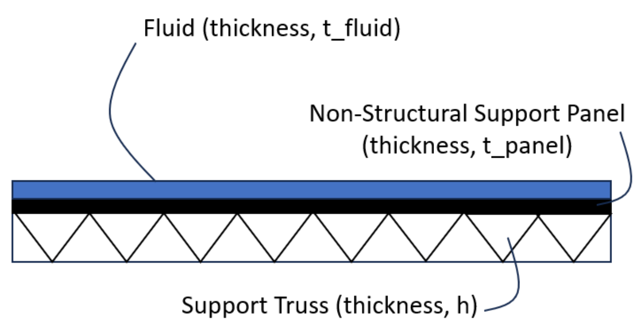


Figure 5. Approximate structural model for first order frequency analysis. The curved frame is modeled as a flat plate with the structural stiffness of an estimated support truss of given depth, h. The areal density is the density of the truss, as well as a non-structural support panel and the fluid layer.

5. VOLUME SCALING

Analysis of the volumetric scaling associated with the three frame archetypes reflects intuitive differences between quadratic and cubic scaling but warrants examination for trade-offs at different scales. Figure 4 examines the volume

and mass scaling of a fluidic mirror with an *f* number of 1, with different aperture radii, and a 5-mm fluid thickness on the curved spherical support frame type. Figure 4(a) shows the fluid volume of each frame archetype with aperture radius. The effect of the cubic versus quadratic scaling can be clearly observed. Figure 4(b) shows the associated fluid mass, assuming gallium, as well as the notional payload mass of a Space X Starship used for the analysis (136,000 kg at time of analysis) and the estimated global annual gallium production in 2021 [11]. Figure 4 (c) shows values for our assumed ionic liquid (IL) with a density of 1200 kg/m^3. The 50-m aperture using gallium is feasible with a single launch, depending on the mass of other system components. However, the percentage of the global gallium supply that would be necessary may present economic challenges to implementation. The mass of the fluid for the curved support frame type scales linearly with fluid thickness (fluid must be thick enough to cover surface defects in the support surface). For a 50-m telescope aperture using frame type C (spherical support surface) and a 5-mm ionic liquid layer, the required fluid mass is about 12,600 kg.

Figure 6 shows the influence of the mirror focal number (*f* number) on fluid volume necessary. We assumed a *f* number of 1, but for use cases that consider other architectures, including other aperture diameters or launch vehicles (discussed in the next section), increasing the focal number can greatly decrease the necessary fluid volume and overall mission mass.

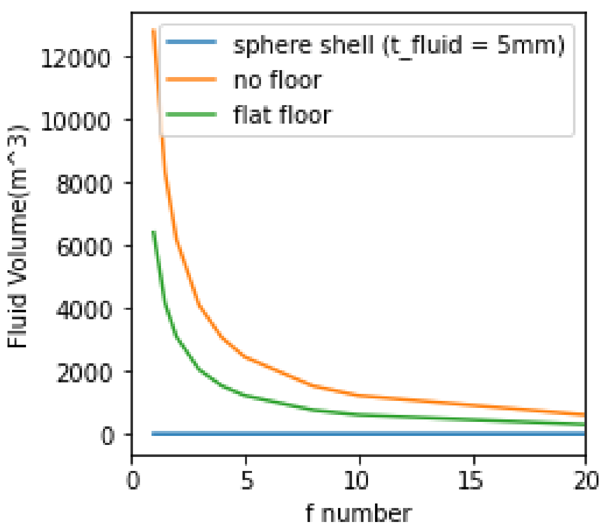


Figure 6. Effect of mirror focal number (*f* number) on fluid volume for each frame archetype (for a 50-m diameter aperture).

Considerations for Apertures Under 10-m Diameter

This work focused on evaluating fluidic mirror technology's potential to enable an order of magnitude increase in aperture size for astrophysics applications. However, there are many reasons to consider apertures smaller than 50 meters. For smaller sizes, considerations beyond launch mass scaling may influence the choice of frame archetype.

One consideration is the effect of the support surface on the overall error of the fluid surface. Though the surface quality will not be affected by the precision of the support surface (the support surface accuracy need only be on the order of the fluid precision), the effect of static errors of the surface on the static shape of the fluid surface may be larger than for a fluidic mirror with only a ring support. For example, in the case of a ring-only frame, the effect of out-of-plane deformation (error) along the ring decays exponentially as a function of its spatial frequency along the frame [2]. How this effect compares to frames with support surfaces remains to be evaluated.

There are other factors as well. The simplicity of a deployable ring without a support surface may justify consideration at smaller aperture sizes. Though the technical readiness level of ionic liquids for mirror surfaces is advancing, for smaller apertures, it is possible that gallium may still offer an alterative. However, these will need to be traded with the other challenges surrounding gallium for both in-flight implementation and pre-launch handling, including ease-of-oxidation, corrosiveness, and the limited options of materials that gallium (and its alloys) can effectively wet.

6. First Order Structural Scaling

To maintain the fluid film, we take as an initial requirement that the structure shall deflect no more than the thickness of the fluid film, targeting 1mm RMS deflection as a safety factor. This represents a lower bound. However, we also evaluate a more stringent requirement to maintain deflections below 10 microns RMS, which we estimate to be an upper bound on the ability of adaptive optics to correct. Table 1 shows the projected disturbances at the L2 orbit, estimated from James Webb Space Telescope station keeping and assuming very slow slewing rates for retargeting. Though the observatory need not be operational during station-keeping and slewing operations, they must not cause film rupture or cause fluid deformations that take too long to settle. Restricting deformation during these operations to what can be accommodated with adaptive optics provides an upper bound estimate on the needed performance.

Table 1. Summary of estimated disturbances for a fluidic telescope in halo orbit at L2. Disturbance magnitudes should be understood as approximate, notional values used for first order analysis.

Disturbance	Estimated Value
Station Keeping @ L2*	~0.003 m/s^2
Gravitational Disturbance @ L2	1.3e-4 m/s^2 [12]
Slew**	10 µRad/s

***Values are estimated from delta V estimations and estimated burn times for the James Webb Space**

Telescope [13], [14]**, biasing towards a low estimate, since for a fluidic telescope, slower station keeping operations are likely tolerable.**

****We assume that very conservative slew rates will be acceptable to maintain fluid stability**

Using Eq. 1 and using the station keeping load as the governing acceleration, this suggests that a 0.28 Hz fundamental frequency system is necessary to keep RMS deflections under 1mm. To keep deflections under 10 micron, a 2.76 Hz structure is needed. Given the coarse nature of the loading estimations, these should be understood as needing a structure on the order of 0.1 Hz to prevent rupture and 1 Hz to maintain fluid stability to acceptable levels under station keeping loads. Under the assumed slewing load, using Eq. 2 for a 50-m aperture telescope, a 1-Hz structure deflects a fraction of a nanometer (6.33e-11 m). A 0.1 Hz structure deflects 633 nm. Both are well within the ability of adaptive optics to compensate. Looking at Eq. 3, the areal density of a fluid telescope renders the deflection due to solar pressure negligible, despite the large aperture size. Gravitational disturbances are important for understanding effects on the fluid layer, but are slowly varying, and thus render accommodation by adaptive optics feasible.

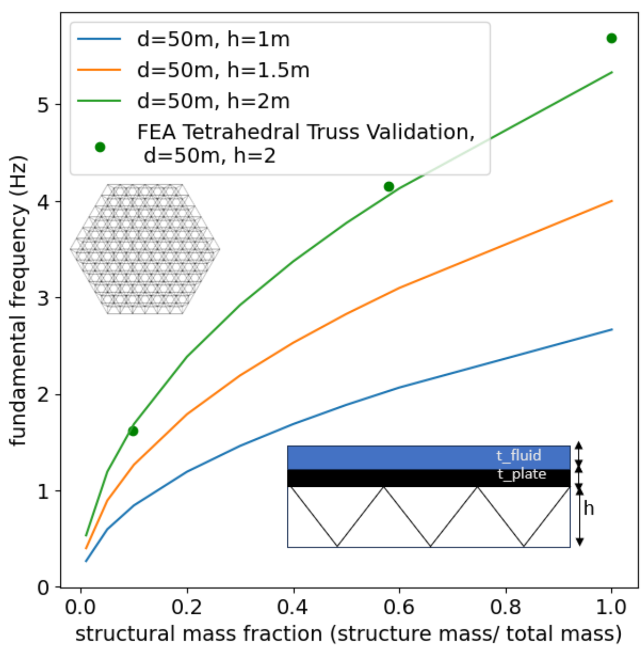


Figure 7. Fundamental frequency of a 50-m diameter tetrahedral truss plates given assumed carbon fiber properties supporting a non-structural 2.5-mm carbon fiber support plate and a 5-mm ionic fluid layer. Limited finite element analysis (FEA) modeling was conducted of a loaded tetrahedral truss to validate the mass estimations of the final analytical model. Results suggest a structure will be able to meet stability requirements at modest structural mass fractions.

We can examine the case of a 50-m telescope, analytically modeled as a tetrahedral truss with 2.5-mm carbon fiber panels (thickness = t_panel) a 5-mm layer of ionic liquid (thickness = t_fluid) as parasitic mass (using Eq. 4). As explained in the model section, we model the curved support structure as a flat tetrahedral support truss with distributed mass. In this case, we do not model the structural contribution of the carbon fiber plate. Thus, this estimate can be considered conservative. Figure 7 shows the fundamental frequency of the modeled plate at different structural mass fractions, for different plate depths. To validate the mass estimations of the analytical relationship, finite element analysis (FEA) modeling was conducted on one plate using the same material parameters described on a tetrahedral truss (shown as an inset on Figure 7). Results show that modest structural mass fractions of a truss support structure should be able to provide sufficient stability (>1 Hz fundamental frequency). Taking a 20% structural mass fraction, we can estimate the support structure mass for 12,600 kg of ionic liquid and 8,925kg of carbon fiber plate to be about 4305 kg. This leads to a total frame + fluid mass estimate of approximately 25,830 kg. Choice of exact structural depth will depend on several factors, including manufacturing and assembly/deployment concept of operations, but these results show acceptable behavior across a range of depth options. While we can expect modest increases in mass from the outer bounding ring, full circular plate, heating elements, fluid distribution lines, and strength safety factors, this provides a baseline mass estimate of what is possible with a rigid structural support. As previously noted, factors such as the curvature of the structure and the carbon fiber support layer can add structural stability, which would reduce the mass needed to meet frequency requirements. A detailed model is the next step towards refining the estimated mass. Figure 8 shows a more detailed concept image of the frame, consisting of a support truss structure with panels that would support the fluid layer.

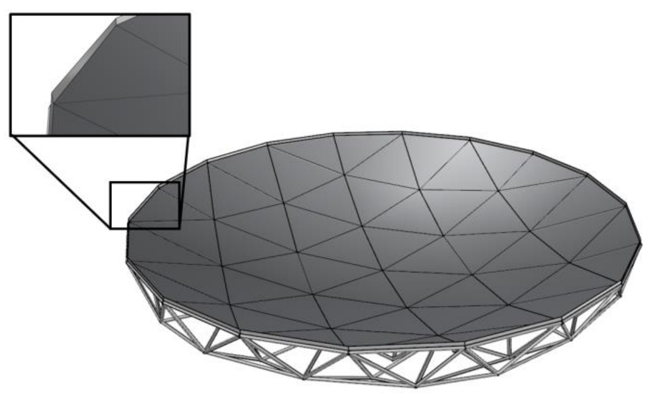


Figure 8. Notional depiction of a rigid support structure with underlying support truss topped with panels. Edge detail shows raised bounding frame element. Triangulation of the surface and the bounding frame can be increased for finer shape fidelity.

Assembly and Deployable Architectures

The preceding analysis focuses on a rigid truss support structure with solid surface support panels. One proposed method for production of this type of structure is robotic assembly. Given ground demonstrations [15]–[17] and planned orbital demonstrations (OSAM-1), we consider this to be technologically feasible, especially since the precision scale necessary (order of 1 mm) is orders of magnitude more than previously demonstrated technology (<100 micron) [18]. Support panels for the surface need not be liquid tight—the nature of the surface tension of the liquid permits non-solid support surfaces, so long as the gaps are sized such that the liquid layer can recover from disturbances. However, integration of fluid deployment lines and heaters may complicate assembled architectures, although with maturation of robotic technologies for in-space servicing, refueling, and assembly, this integration should be possible.

Alternatively, hybrid deployed and assembled architectures could be considered, where the underlying tetrahedral truss structure [19] or circular bounding ring could be deployed, with robotically assisted placement of surface components.

Purely deployable architectures could also be considered, though scalability may be a challenge. Though some deployable architectures feature solid surfaces [20]–[22], deployable architectures demonstrated at the 50-m scale typically rely on a tensioned membrane or mesh surface (again, the membrane need not be solid given surface tension). Lake et al. [6] established that the mass scaling of a tetrahedral truss support and a tensioned membrane is approximately equal. However, this assumes that the tension in the membrane can be scaled directly with the buckling strength of the bounding ring structure (directly scaled with areal density). The analysis in [6] is directed at gossamer space telescope concepts that have a much lower areal density than a fluidic telescope (for the ionic liquid, a 5-mm fluid layer is 6 kg/m^2, whereas many tensioned deployables use meshes that are on the order of 50 g/m^2). The tension of this membrane for the high areal density of the fluid telescope may not be scalable due to limitations on the forces that deployment mechanisms can apply, tension cables can withstand, or the strength of available materials (since to meet the same fundamental frequency, the tension in the membrane would need to scale directly with the areal loading). Additionally, the analysis in [6] calculates the frequency of the tensioned membrane assuming that the bounding ring structure provides a perfectly rigid bounding condition, a potentially flawed assumption at the 50-m scale and the associated mass limitations. For these reasons, we leave investigation of tensioned membrane deployable architectures to future work. Despite potential scaling challenges, we believe deployable architectures may be strong candidates for smaller apertures or technology demonstration missions of fluidic mirrors.

7. Conclusion

Fluidic shaping offers a novel methodology for creating telescope primary mirrors an order of magnitude larger than current capability, while decoupling mirror surface precision from frame manufacturing precision. Because of the density of the fluid, structural support for a fluidic mirror offers a unique challenge when compared to typical telescope support structures and other space structures that take similar shapes. For large apertures > 10 m diameter, a frame architecture that features a curved support surface in the center of a bounding ring is necessary for mass feasibility.

Analysis of expected disturbance loads shows that a 50-m diameter fluidic telescope can be supported with sufficient stability by a truss structure with a curved segmented surface to support the fluid mass. We estimate conservatively that such a support architecture can yield a total frame + fluid mass of <26,000 kg for a 50-m aperture, leaving a reasonable mass budget for other mission components (sunshade, instrumentation, primary spacecraft bus, etc.) based on expected heavy launch vehicles (e.g., SpaceX Starship or NASA SLS) launch and refueling capabilities.

While this analysis shows baseline feasibility, maturing the architecture will provide additional constraints. Detailed design of the support structure will further refine mass estimates. Future work will explore potential deployable frame options to trade against this rigid truss support design that can be enabled by robotic assembly.

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